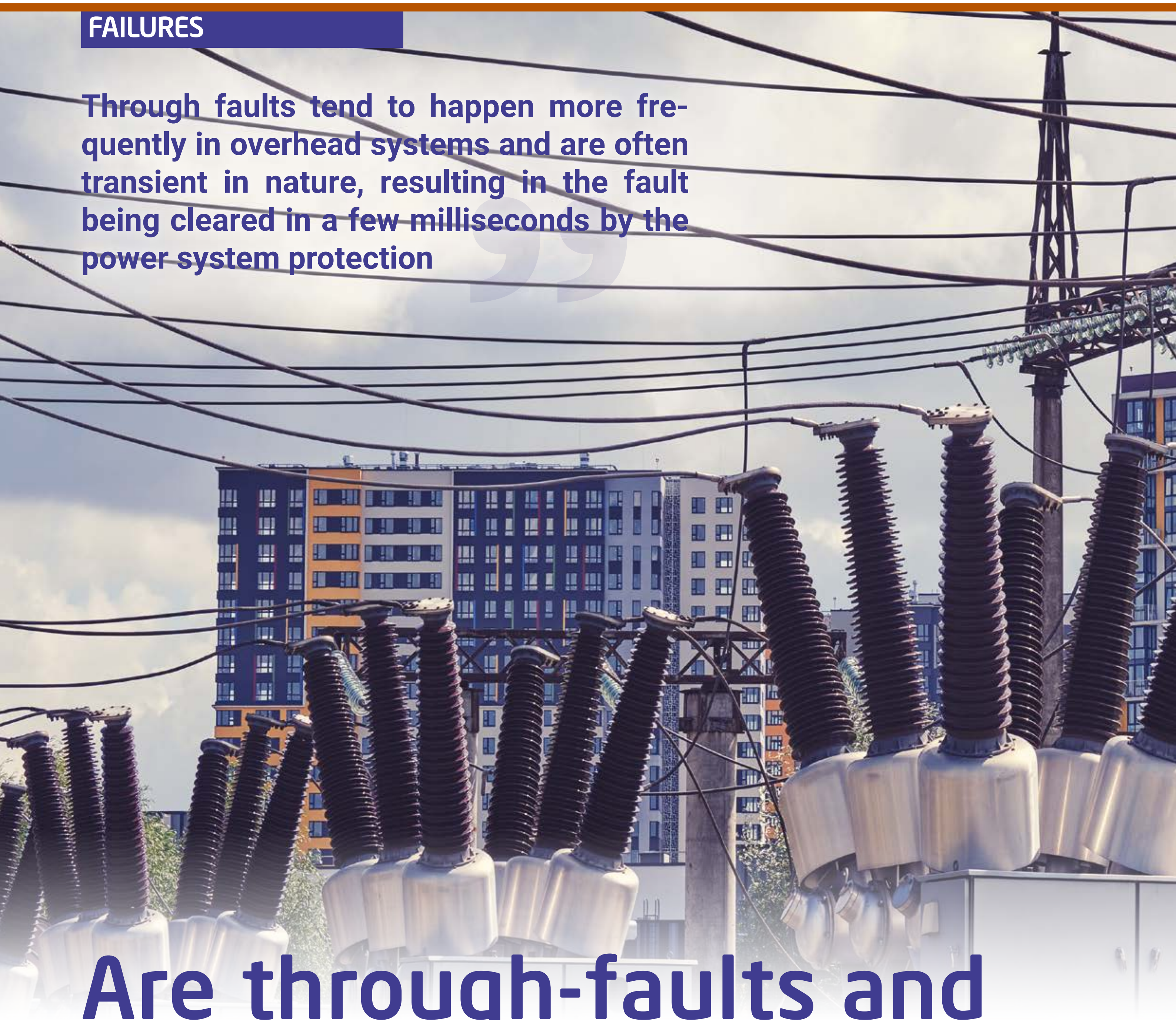
Through faults tend to happen more frequently in overhead systems and are often transient in nature, resulting in the fault being cleared in a few milliseconds by the power system protection



Are through-faults and slow breakers damaging your transformer?

ABSTRACT

Much research and testing has been focused on the question: how much life remains in my transformer? Testing for furans dissolved in the oil to infer the average DP of the paper insulation on the conductors of the windings has been a focus for many years. While this offers some value, furans, by their nature, are volatile and can escape during any oil processing carried out. Therefore, it cannot be considered as a single test to make major decisions on the remaining life of a transformer.

There remains the need for further information on operation of a transformer in service to understand not just the chemical reactions taking place inside the tank, but what EXTERNAL events influence the mechanical damage sustained by the windings and the clamping structure.

These externally induced events include the impact of harmonics, through-faults, and slower than normal breaker operation.

KEYWORDS

breakers, harmonics, damage, transformer aging, through-faults

1. Harmonics

The increasing implementation of renewable energy resources connected (most of the time) into an existing distribution or sub-transmission network that was never designed to handle a two-way power flow presents an opportunity for accelerated aging of the paper insulation surrounding the conductors of the windings. These generation sources (which are often inverter-fed) together with geomagnetically induced currents (GIC), are two of the factors known to introduce undesirable harmonic frequencies into the grid and the equipment connected to it.

A recent article from Transformers Magazine, Volume 7, Issue 2, April 2020, *Managing Existing Transformers in the Grid Transition* [1], goes into deeper details, with case histories presented and explained. One of the items mentioned is a suggestion that managing existing units in these applications will require an increased level of condition monitoring, from the aspect of the rate of insulation aging and accumulation of the harmonic content, which is now available with some online monitoring systems.

2. Through-faults

Potential generation of through-faults can vary greatly across short spans of any electrical grid, and factors such as circuit length, type (overhead, underground), condition of protective equipment, degrading infrastructure, and terrain must be considered as factors that can affect the frequency of fault occurrences. Faults are generally the result of a low impedance path to the ground being introduced into a circuit, such as dielectric failure of protection equipment or tree limbs striking overhead lines and causing the current to exceed the transformer's rated base.

Underground systems are designed to limit exposure to potential fault sources. However, when these underground faults do occur, they are usually persistent, causing a lockout of the protection system, which requires a closer investigation before power can be restored. These faults

The amount of energy flowing through the transformer during through faults places excessive mechanical and thermal stresses on the core and coil assembly of the affected transformer

tend to happen more frequently in overhead systems and are often transient in nature, resulting in the fault being cleared in a few milliseconds by the power system protection.

The amount of energy flowing through the transformer (I^2T) for the duration of these transient faults places excessive mechanical and thermal stresses on the core and coil assembly of the affected transformer. However, due to the power-protection system operating effectively, little consideration is given to the weakening of the transformers clamping system or any core deformation that may have occurred because of the increased electromagnetic force.

It is difficult to quantify the level of cumulative I^2T a specific transformer can sustain and remain fit for service due to the wide range of variables that must be considered when performing the assessment

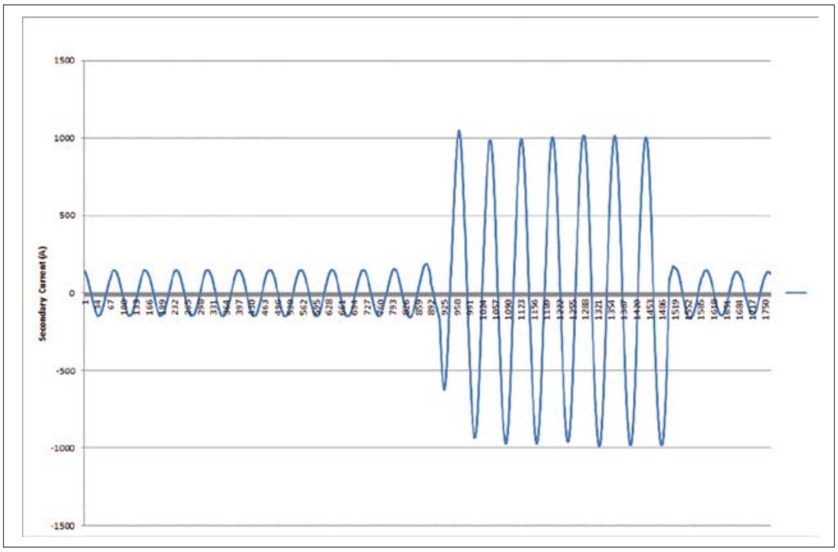


Figure 1. Seven cycles 60 Hz at four times nominal RMS

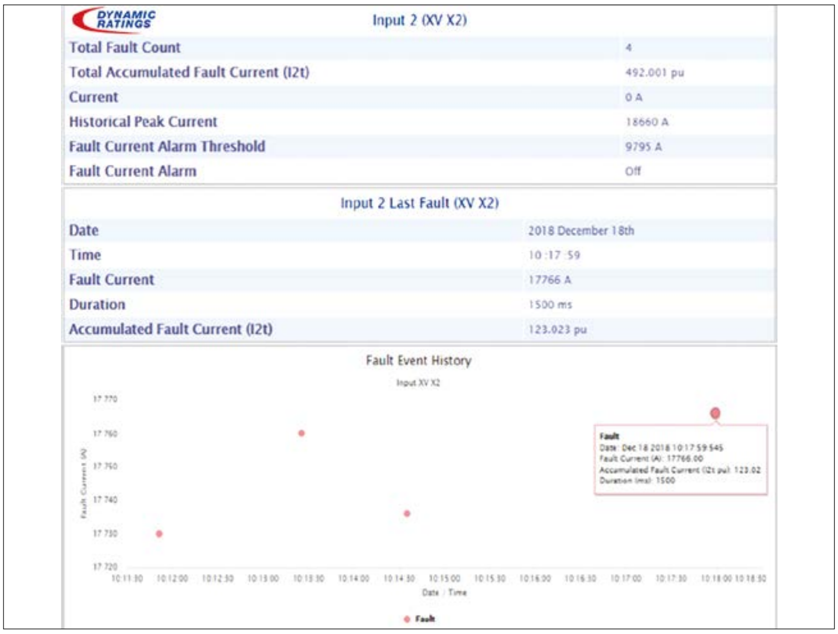


Figure 2. Example of fault counting on the transformer monitor

The frequency at which these events occur can have an aggregated effect (cumulative I^2T) on the transformer's mechanical structure, ultimately resulting in a decrease of the transformer's fault withstand capability. The presence of these cumulative effects is problematic in that they are not easily detected using routine maintenance testing such as power factor and dissolved gas or furan analysis but would require more in-depth testing procedures such as sweep frequency response analysis or winding induction testing.

Nor are existing vintage electro-mechanical relays much help to understand the amount and duration of through faults. They react as designed to disconnect a load (transformer, generator, etc.) in a preset amount of time. They do not have the capability of modern digital relays that can capture the events. However, many existing substations have not had these relays replaced with digital type protection relays, and even when the digital relays are present, asset managers are often not able to access the quantitative data required to evaluate the damage.

Fig. 1 is an example of a seven-cycle fault with an RMS at four times nominal captured and displayed via a through-fault and harmonics card on a transformer monitoring system web page.

Though this graph illustrates a seven-cycle fault, power-protection systems generally require a minimum of three cycles to clear excessive fault current. The fault detected was on a long feeder with low fault levels in the area. None the less it provides a record of faults on the transformer.

It is difficult to quantify the level of cumulative I^2T a specific transformer can sustain and remain fit for service due to the wide range of variables that must be considered when performing the assessment. The knowledge that a particular transformer experienced excessive through-fault levels could trigger a decision to perform more in-depth testing such as a sweep frequency response analysis.

This would allow for slight deformations of the core and coil assembly to be identified, which would be undetectable by more routine testing methods. Through-faults are a common occurrence on most electrical systems, yet the cumulative effects of these events, which can reduce the withstand capability of a transformer's mechanical systems, are rarely taken into consideration when determining the overall equipment condition.

The data provided by the transformer monitoring system (see Fig. 2) with through-fault and harmonics monitoring raises awareness of through-fault and harmonic distortion's cumulative values, allowing for proactive testing and maintenance to be implemented before transformer failure occurs.

3. Increased risk due to slow operation of circuit breakers

A key and mandatory component of any electrical circuit is the circuit breaker. Circuit breakers are relied upon to protect power systems from abnormal electrical conditions. They are found in the power system from distribution substations to high voltage transmission systems. They provide protection against fault current and are also used for transferring loads and controlling capacitor banks and other VAR compensating equipment, ensuring steady power factor and system reliability.

Circuit breaker maintenance is a highly critical task in safeguarding the reliability and safety of any power system. Ensuring they will perform their function requires periodic inspections and testing. The issue has always been when to perform this necessary function. It usually requires an outage to test circuit breaker functionality, and often these outages are not easily made available.

The circuit breaker failures can be broken down into five categories: mechanical, low SF6 pressure or loss of stored energy in pneumatic and hydraulic operators, trip coil problems, and bushing failure. The graph in Fig. 3 relates the percentages.

4. Limiting through-fault exposure to transformers and other equipment

Online circuit breaker monitoring has proven to be highly effective at detecting operational abnormalities that may often go unobserved through traditional maintenance testing. Interrupting time is one of the most critical components of circuit breaker operation that is more easily observed using online monitoring. Using this method improves the detection of breakers for which the interrupting time has exceeded the acceptable rating for that equipment.

This is often missed with routine maintenance, as any operation of the circuit breaker prior to recorded testing can result in misleading timing results, as the initial operation (generally referred to as the First Trip) tends to break loose components of the lubrication and bearings, thereby making the circuit breaker look as though it is functioning within operational parameters.

This misinterpretation of the circuit breaker's performance is critical as slow interrupting times greatly increase the duration to which transformers are exposed to excessive fault current, effectively aging the transformer prematurely as cumulative fault values are a product of both current amplitude and duration. Increases in either of these values place excessive thermal and mechanical wear on the transformer.

Circuit breaker maintenance is a highly critical task in safeguarding the reliability and safety of any power system

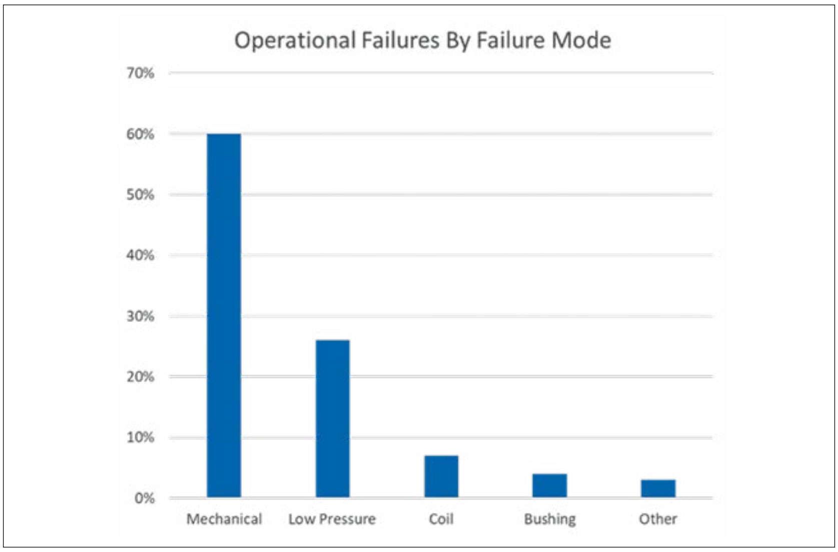


Figure 3. Percentage of failure modes

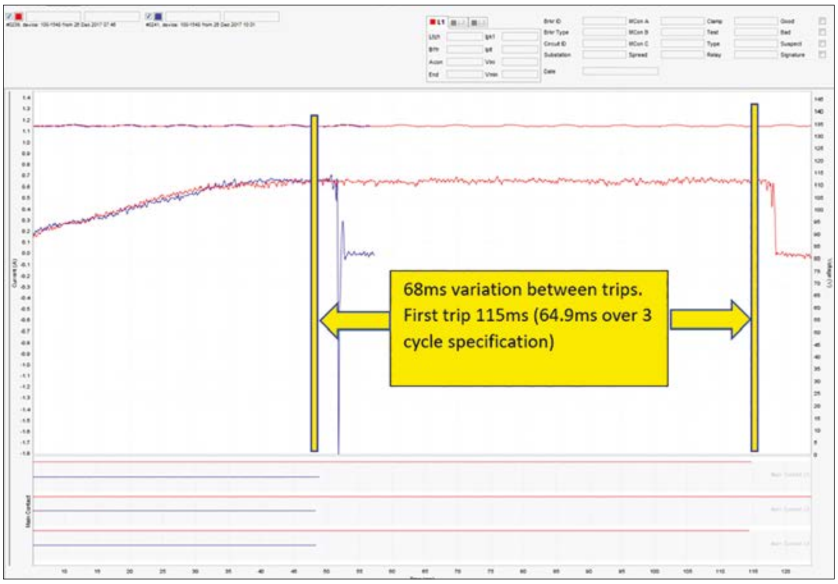


Figure 4. Breaker slow opening time difference

Figure 5. Complete failure of transformer and breaker

Online circuit breaker monitoring has proven to be highly effective at detecting operational abnormalities that may often go unobserved through traditional maintenance testing

Fig. 4 provides an illustration of a circuit breaker that is beginning to demonstrate slow opening times. While this is a minor failure, as the breaker would still be able to perform its primary job of clearing the fault, without interventive maintenance, it is likely that breaker functionality will degrade to the point of causing a system event.

- The first trip exceeds specified limits for this circuit breaker.
- The second trip is 68 ms faster than the first trip (an indicator of lubrication degradation).
- Noisy signal at the auxiliary contact operation indicates a potential problem developing with auxiliary contacts.

5. A situation of an inoperable breaker, and the result

An example of the failure to detect the slowing of circuit breakers rated interrupting times during time-based inspections and testing could eventually lead to lubrication and wear of the mechanism components, where they become degraded to the point that the breaker is rendered inoperable.

The photographs in Fig. 5 illustrate a complete failure of a transformer and the resulting fire in the control room due to a high-side transmission breaker failing to operate.

During this event, the fault is thought to have occurred somewhere on the low-side bus, between the bank breaker and the transformer. The relay for the high-side breaker issued a trip signal to the circuit breaker, which failed to open.

Due to the distance between stations, fault levels were too low to cause a transmission breaker trip at the upstream station, leaving the fault present on the transformer for over six minutes and ultimately resulting in the transformer failure and fire in the control house. The misoperation of the circuit breaker was determined to be caused by a seized main bearing of the operating mechanism, despite this circuit breaker having passed inspection four years before this event occurred.

The failure of the high-side transmission breaker operation may lead to the complete failure of a transformer and with the fire in the control room

6. Conclusion

Measuring and tracking the harmonic content of both voltage and current is recommended for existing transformers connected to DER where inverters are in place. The Loading guide IEC 60076-1/ 2012 includes the definition of normal service conditions in section 4.2 [3].

The wave shape of the supply voltage:

A sinusoidal supply voltage with a total harmonic content not exceeding 5 % and an even harmonic content not exceeding 1 %.

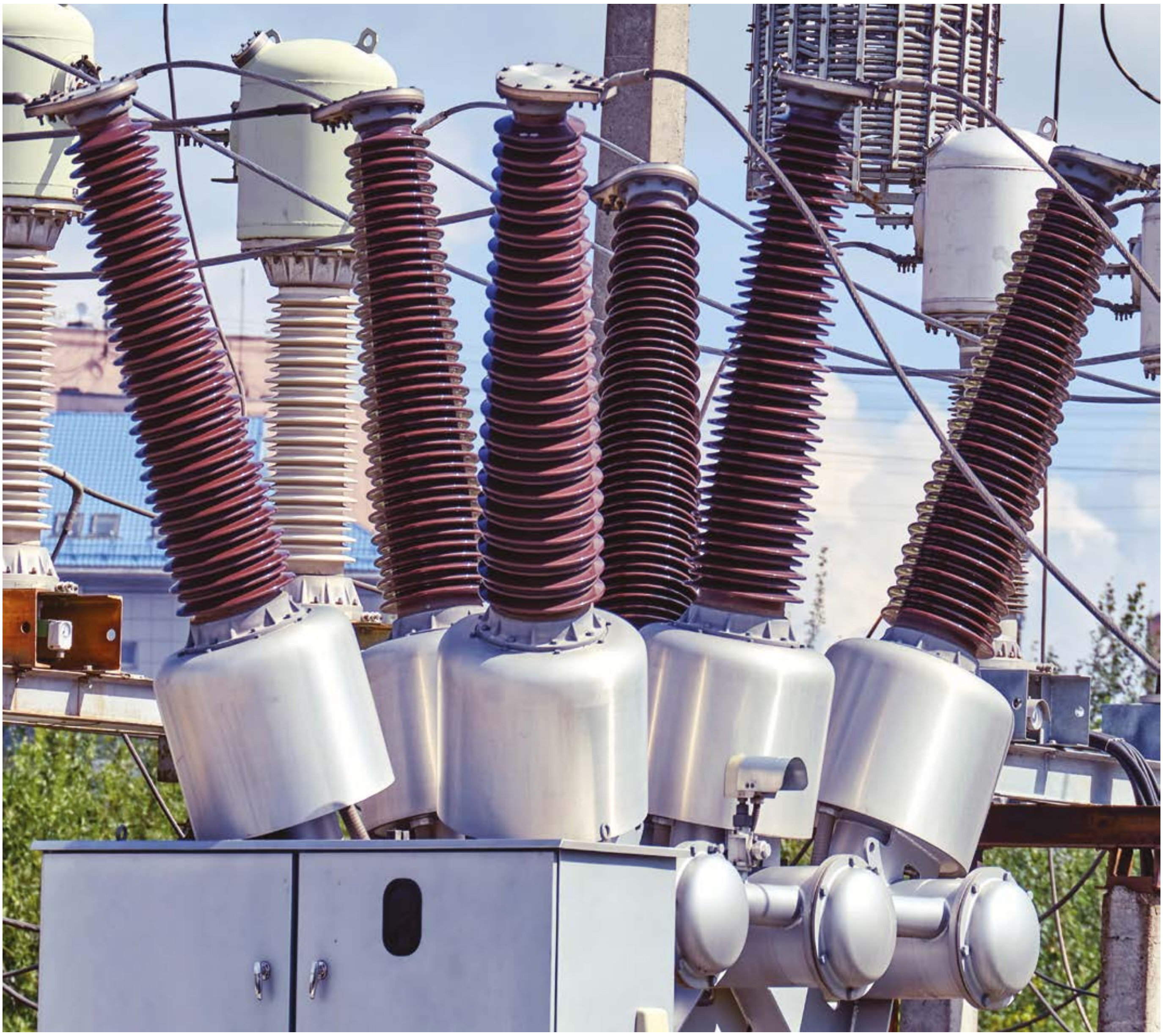
Load current harmonic content:

The total harmonic content of the load current not exceeding 5 % of the rated current.

Transformers can operate at rated current without excessive loss of life with a current harmonic content of less than 5 %. However, it should be noted that the temperature rise will increase for any harmonic loading and may exceed the rated temperature rise. This will have the impact of accelerating the aging rate of the paper insulation on the conductors.

Due to aging equipment and decreased operating budgets, effective circuit breaker management by means of offline testing and time-based maintenance has proven to be increasingly ineffective. The impact usually results in increased clearing times or not at all in some cases of the associated breakers resulting in a greater number of unplanned outages and the premature aging or failure of substation equipment, including transformers, due to higher levels of cumulative through-fault exposure.

Through the utilisation of online monitoring, many of the failure conditions common to circuit breaker failure could be detected before an event occurs. This allows maintenance resources to be directed towards preventing the occurrence of substation events as opposed to responding to unplanned emergency outages, allowing for extended equipment service life and a reduced impact on the transformer aging.



Acknowledgements

The author wishes to express his gratitude for the technical input of Chris Rutledge of Dynamic Ratings.

Bibliography

[1] Brian Sparling, *Managing existing transformers in the grid transition,* Transformers Magazine, Volume 7, Issue 2, 2020

[2] Chris Rutledge, *Breaker monitoring: improving reliability through directed maintenance,* TechCon North America, February 2020

[3] Constantin Moldoveanu, Dr. Ing., *Considerations on the feasibility of certain technical provisions of IEC 60076-1/2012 standard*

Measuring and tracking the harmonic content of both voltage and current is recommended for existing transformers connected to DER where inverters are in place

Authors

Brian D. Sparling, a Senior Member of IEEE, is a Senior Technical Advisor with Dynamic Ratings. Brian has over twenty years of experience in the field of power and distribution transformers. For the last 28 years, he has been involved in all aspects of online monitoring, diagnostics, and condition assessment of power transformers. He has authored and co-authored more than 33 technical papers on several topics dealing with the monitoring and diagnostics of transformers. He has worked on many guides and standards with the Canadian Electricity Association, IEEE Transformers Committee and, the CIGRÉ A2 Transformer committee.